

June 24, 2002



# Acquisition

V-22 *Osprey* Hydraulic System  
(D-2002-114)

Department of Defense  
Office of the Inspector General

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### **Acronyms**

EMD	Engineering and Manufacturing Development
FMECA	Failure Modes, Effects and Criticality Analysis
FREST	Fleet Replacement Enlisted Skills Training
FST	Fleet Support Team
IPT	Integrated Product Team
JAGMAN	Judge Advocate General Manual
LRIP	Low-Rate Initial Production
MTBF	Mean Time Between Failure
NAVAIR	Naval Air Systems Command
OPEVAL	Operational Evaluation
USD (AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics



INSPECTOR GENERAL  
DEPARTMENT OF DEFENSE  
400 ARMY NAVY DRIVE  
ARLINGTON, VIRGINIA 22202-4704

June 24, 2002

MEMORANDUM FOR NAVAL INSPECTOR GENERAL

SUBJECT: Evaluation Report on V-22 *Osprey* Hydraulic System  
(Report No. D-2002-114)

We are providing this report for your information and use. We considered management comments on a draft of this report when preparing the final report.

Comments on the draft of this report conformed to the requirements of DoD Directive 7650.3 and left no unresolved issues. Therefore, no additional comments are required.

We appreciate the courtesies extended to the staff. Questions should be directed to Mr. Donald A. Bloomer at (703) 604-8863 (DSN 664-8863) (dbloomer@dodig.osd.mil) or Mr. Richard A. Brown at (703) 604-8849 (DSN 664-8849) (rbrown@dodig.osd.mil). See Appendix D for the report distribution. The team members are listed inside the back cover.

*David K. Steensma*  
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Acting Assistant Inspector General  
for Auditing

## Office of the Inspector General of the Department of Defense

**Report No. D-2002-114**

(Project No. D2001LA-0124)

**June 24, 2002**

### **V-22 *Osprey* Hydraulic System**

#### **Executive Summary**

**Who Should Read This Report and Why?** DoD civilian and military personnel involved with the design and development of new systems will find these issues in reliability data helpful in improving their own areas of product development.

**Background.** The V-22 *Osprey* Joint Advanced Vertical Aircraft (the V-22) is a tiltrotor, vertical takeoff and landing aircraft, which was developed to fulfill multi-Service operational requirements. The V-22 design incorporates advanced technologies in composite materials, digital avionics, fly-by-wire controls, and survivability. It operates as a helicopter for takeoffs and landings and, once airborne, converts to a turboprop aircraft for distance flight. That conversion capability is accomplished through the tilting or rotation of a nacelle mounted at the end of each wing. Each nacelle is equipped with an engine and transmission that drives a rotor with a diameter of 38 feet. The V-22 hydraulic system, which comprises three independent subsystems, provides hydraulic power to the V-22 rotor system controls and control surfaces.

**Results.** Additional oversight and maintenance training measures were needed to improve the reliability of the hydraulic system for the V-22 *Osprey*. The V-22 entered the Low-Rate Initial Production phase in 1997 with a hydraulic system that performed at reliability rates significantly lower than predicted in the design process. During the Engineering and Manufacturing Development phase, the system achieved no better than 38.2 percent of the predicted reliability rate. The V-22 was produced with a less-than-optimal hydraulic system because the V-22 Program Manager (PMA-275) did not exercise sufficient oversight of the hydraulic system's design: PMA-275 did not specifically monitor the reliability rates of the hydraulic system's performance. In addition to previously mandated design changes, other actions are needed to ensure sufficient management focus on the V-22 hydraulic system's performance and maintenance. A program to monitor the V-22 hydraulic system's performance, especially component reliability rates, on a continual basis will improve the reliability of the hydraulic systems. Also, Bell Helicopter Textron, Inc., should amend course materials for the V-22 maintenance course to include the unique characteristics and hazards of the titanium hydraulic lines. Similarly, the Technical Study Guide Program for Marine Medium Tiltrotor Training Squadron 204 should be amended to expand the discussion of titanium hydraulic lines. (See the Finding section for the detailed recommendations.)

**Management Comments.** The Assistant Secretary of the Navy (Research, Development, and Acquisition) concurred with the recommendations. The Assistant Secretary stated that new hydraulic system reliability predictions were established and a dedicated team was established to monitor actual performance. The Navy was also

updating its Technical Study guide program to emphasize the unique characteristics and considerations regarding conducting maintenance actions in the vicinity of titanium hydraulic lines. See the Finding section of this report for a summary of management comments and the Management Comments section for the complete text.

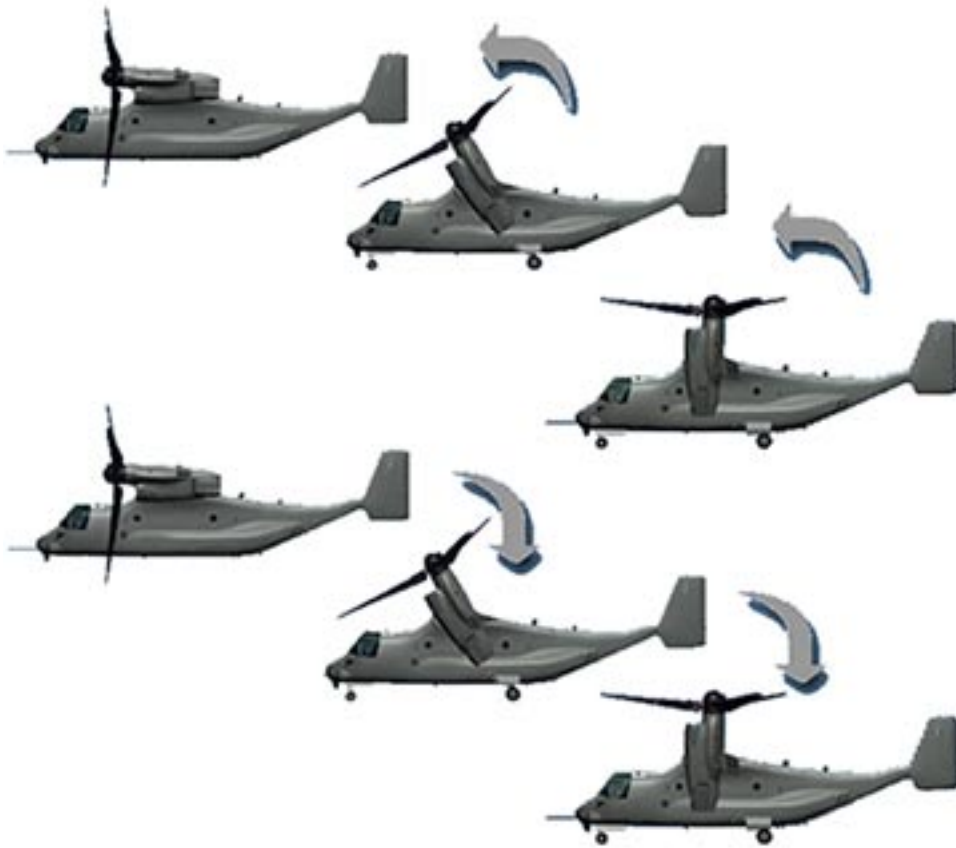
**Management Initiatives.** After a fatal accident in December 2000, the V-22 was grounded and PMA-275 began several initiatives, including the establishment of the Line Clearance Integrated Product Team and the Senior Hydraulic System Review Team (the Senior Hydraulic Team), to identify and correct the hydraulic system challenges facing the V-22.

- The Line Clearance Integrated Product Team was established to identify, document, and study line clearance issues in the V-22 nacelles. The team concluded that poor access, chafing (both under clamps and throughout the nacelle) because of insufficient clearances, and excessive maintenance hours per flight hour were major problems.
- The Senior Hydraulic Team was assembled to provide a thorough and independent technical review of the V-22 hydraulic system's architecture, including system design and validation. The team concluded that the nacelle was a key problem area because of, among other factors, installation flaws, a lack of clearances, difficulty in inspecting hydraulic lines and installing or replacing components, and too many variances from one aircraft to another. Hydraulic line failure caused by chafing from a wire bundle was deemed a safety of flight issue. The team made numerous recommendations, to include prohibiting wire bundles from being clamped to the hydraulic lines.

# Table of Contents

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<b>Executive Summary</b>	i
<b>Background</b>	1
<b>Objectives</b>	4
<b>Finding</b>	
Reliability of the V-22 Hydraulic System	5
<b>Appendixes</b>	
A. Scope and Methodology	18
B. Prior Coverage	21
C. Learning Curve Calculations	22
D. Report Distribution	24
<b>Management Comments</b>	
Department of the Navy	27



(Source: Bell Boeing)

Figure 1. The aircraft shown above illustrate the rotation of the V-22 nacelles, converting the V-22 from helicopter mode to airplane mode (the top three aircraft) and from airplane mode to helicopter mode (the bottom three aircraft).



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## Background

The V-22 *Osprey* Joint Advanced Vertical Aircraft (V-22) is the world's first tiltrotor, vertical takeoff and landing aircraft in production. Its design incorporates advanced technologies in composite materials, digital avionics, fly-by-wire controls,<sup>1</sup> and survivability. The V-22 combines the vertical takeoff and landing characteristics of a helicopter with the speed and range of a turboprop aircraft. The V-22 operates as a helicopter for takeoffs and landings and, once airborne, converts to a turboprop aircraft for distance flight. That conversion capability is accomplished through the tilting or rotation of a nacelle mounted at the end of each wing. Each nacelle is equipped with an engine and transmission that drives a rotor with a diameter of 38 feet.

The V-22 hydraulic system, which comprises three independent subsystems, provides hydraulic power to the V-22 rotor system controls and control surfaces. All three subsystems contain a network of hydraulic tubes and hoses (hydraulic lines) that supply hydraulic fluid and pressure to each subsystem's respective components. The design results in a triply redundant hydraulic system, provided there are no failures in common hydraulic lines of the three subsystems. If a loss of hydraulic pressure or fluid is detected, the aircraft's software, together with specially designed hardware, automatically isolates the defective system. However, the system is only doubly redundant along 24 common hydraulic lines in each nacelle. The common lines are between the switching isolation valves, local switching-isolation valve, and the swashplate actuators. Because failures in those common hydraulic lines cannot be isolated, a failure of a common line degrades performance of a primary hydraulic system and the backup hydraulic system in that nacelle.

The V-22 was developed to fulfill multi-Service operational requirements and has three variants:

- the Marine Corps MV-22, used for combat assault and assault support;
- the Air Force CV-22, used for special operations missions; and
- the Navy HV-22, used for combat search and rescue, special warfare, and fleet logistical support.

This report uses the term V-22 generically; the hydraulic systems are the same for all of the variants.

**History of V-22 Program Management.** The V-22 Program started in December 1981 and was managed by the Army until it was transferred to the Navy in December 1982. When the program came under the Navy's acquisition

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<sup>1</sup> A fly-by-wire flight control system uses computers to transmit pilot inputs as electrical signals through wires to actuators that move the control surfaces that maneuver the aircraft. In contrast, a mechanical flight control system uses direct mechanical linkages to transmit pilot inputs to the control surfaces.

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management, the Naval Air Systems Command (NAVAIR) became the host command. The Program Executive Officer, Air Anti-Submarine Warfare, Assault, and Special Mission Programs, who reports to the Assistant Secretary of the Navy (Research, Development, and Acquisition), established the V-22 Program Manager (PMA-275) to manage the V-22 Program. The primary mission of PMA-275 was to provide DoD operating forces with a fully developed, reliable, and supportable advanced vertical takeoff and landing aircraft capable of satisfying operational requirements.

Oversight and execution of the V-22 acquisition program is accomplished using the Integrated Product Team (IPT)<sup>2</sup> concept. The leadership team, an overarching IPT led by PMA-275, comprises representatives from various NAVAIR functional competencies. The leadership team focuses on the strategic direction of the V-22 Program and is augmented by functionally aligned, working-level IPTs. Each of those IPTs has a “Lead” and is staffed with a combination of PMA-275 employees and representatives from appropriate NAVAIR functional competencies. Together with their counterparts from the *Osprey*’s dual prime contractors, Bell Helicopter Textron, Inc., and Boeing Helicopters Division (Bell Boeing), the leadership team and working-level IPTs work jointly in support of the development, test and evaluation, procurement, initial support, and readiness improvement of the V-22.

**Progression of the V-22 Program.** In 1986, the Navy obtained approval from the Defense System Acquisition Review Council, which was chaired by the Under Secretary of Defense for Acquisition and Technology (now the Under Secretary of Defense for Acquisition, Technology, and Logistics [USD(AT&L)]), to enter into the Full-Scale Development phase. The Navy awarded a contract to Bell Boeing to design and produce six aircraft for flight and ground testing. The first flight of the V-22 took place in March 1989. In October 1992, the Navy entered the Engineering and Manufacturing Development (EMD)<sup>3</sup> phase, awarding Bell Boeing an EMD contract for four preproduction V-22 aircraft.

In an April 25, 1997, Acquisition Decision Memorandum, the USD(AT&L) approved the Marine Corps variant of the V-22 to enter the Low-Rate Initial Production (LRIP)<sup>4</sup> phase. The memorandum also delegated milestone decision

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<sup>2</sup> An IPT is a functionally aligned team comprising representatives from all appropriate disciplines and assembled to work together to build successful and balanced programs, identify and resolve issues, and make sound and timely recommendations to facilitate decision-making.

<sup>3</sup> The objective of the EMD phase in the acquisition process is to translate the most promising design approach into a stable, interoperable, producible, and cost-effective design; to validate the manufacturing process; and to demonstrate system capabilities through testing. The intended output of the phase is, at a minimum, a preproduction system that closely approximates the final product, documentation necessary to enter the production phase, and test results that demonstrate the production product will meet stated requirements.

<sup>4</sup> LRIP is the production of a system in limited quantities to provide systems for additional operational test and evaluation, to establish an initial production base, and to permit an orderly increase in the production rate sufficient to lead to Full-Rate Production upon successful completion of operational testing.

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authority<sup>5</sup> for the V-22 Program to the Navy. Since April 1997, 10 LRIP aircraft have been built and accepted into the V-22 Program. According to PMA-275, as of December 31, 2001, program costs for the V-22 were estimated at \$46 billion (in FY 1986 dollars). Of that \$46 billion, \$40.7 billion was for the Navy and Marine Corps and \$5.3 billion was for the Air Force.

During its operational evaluation (OPEVAL),<sup>6</sup> November 1999 through July 2000, the V-22 demonstrated that it could carry 24 combat-equipped soldiers or a 10,000-pound load, achieve true airspeed of 248 knots in flight, and travel 2,113 nautical miles with a single aerial refueling. However, in the “Combined Operational Test and Evaluation and Live Fire Test and Evaluation Report on the V-22 *Osprey*,” November 17, 2000, the Director, Operational Test and Evaluation concluded that the V-22 was operationally effective but was not operationally suitable. The Director stated that the V-22 “demonstrated marginal mission reliability.” The Director’s conclusion that the V-22 was not operationally suitable was based, in part, on the failure rates related to the hydraulic system experienced during the OPEVAL.

On December 11, 2000, four Marines were killed when an LRIP V-22 crashed in Jacksonville, North Carolina, during a routine training mission. The Panel to Review the V-22 Program (the Panel),<sup>7</sup> in its report of April 30, 2001, stated that, based on preliminary results from the Aircraft Mishap Board and the February 23, 2001, Judge Advocate General Manual investigation report (the JAGMAN Report), the mishap had resulted from a hydraulic line failure and a flight control system software anomaly that occurred when the pilot pressed the flight control reset button. The report of the Panel also stated that neither the failure nor the anomaly alone would have caused the accident, but the combination had resulted in a loss of flight control. As a result of the mishap, the Commandant of the Marine Corps and NAVAIR jointly suspended V-22 flight operations on December 12, 2000.

In May 2001, the USD(AT&L) reassumed the milestone decision authority for the V-22 Program. On December 21, 2001, the USD (AT&L) announced a number of decisions regarding the V-22. Specifically, the USD (AT&L) stated that test flights for the V-22 would resume in April 2002, provided that a joint Secretary of the Navy and USD (AT&L) review to “assess the basis and confidence” for resuming those flights did not disclose anything that would suggest the need to change that time frame. In addition, pending a review of the technical progress of the program during flight testing, the USD(AT&L) approved limited production at minimum sustaining levels.

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<sup>5</sup> The individual designated, in accordance with criteria established by the USD(AT&L), to approve entry of an acquisition program into the next phase of the acquisition process.

<sup>6</sup> An OPEVAL is used to test and analyze a specific end item or system under Service operating conditions, as far as practical, to determine whether quantity production is warranted.

<sup>7</sup> The Panel, composed of two retired military pilots with combat flying experience, one aeronautical engineer from industry, and one aerospace engineer from academia, was chartered to examine the relevant factors related to safety and combat effectiveness of the V-22.

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The V-22 Program remains in the LRIP phase of the acquisition cycle. Of the four EMD aircraft produced, two are located at Naval Air Station Patuxent River, Maryland, for continued developmental testing in support of fostering the V-22 Program's progression to Milestone III (Full-Rate Production). The other two EMD aircraft have been modified for use in the CV-22 development and systems integration program based at Edwards Air Force Base, California. Of the 10 LRIP aircraft accepted into the V-22 Program, seven<sup>8</sup> are assigned to the Marine Medium Tiltrotor Training Squadron 204 (VMMT-204) at Marine Corps Air Station New River, North Carolina. The USD (AT&L) approved the V-22 to resume flight testing, and on May 29, 2002 the V-22 flight testing resumed.

## Objectives

This project started as an audit assist to an investigation by the Defense Criminal Investigative Service, Office of the Inspector General of the Department of Defense. During that process, we determined that additional work was needed to assess the V-22 hydraulic system's performance and we began this evaluation.

The overall evaluation objective was to assess the hydraulic system of the V-22. Specifically, we reviewed the system's performance throughout the Full-Scale Development, EMD, and LRIP phases of the acquisition process. In addition, we evaluated management actions as they related to the hydraulic system. See Appendix A for a discussion of the evaluation's scope and methodology and Appendix B for prior coverage.

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<sup>8</sup> LRIP V-22 (Bureau No. 165436) was lost in an April 8, 2000, mishap unrelated to hydraulics. LRIP V-22 (Bureau No. 165440) was lost in the December 2000 mishap. LRIP V-22 (Bureau No. 165433) was predestinated as a maintenance trainer and transferred in July 2001 to the V-22 Fleet Replacement Enlisted Skills Training.

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## Reliability of the V-22 Hydraulic System

The V-22 *Osprey* entered the LRIP phase in 1997 with a hydraulic system that performed at reliability rates significantly lower than predicted in the design process. During the EMD phase, the system achieved no better than 38.2 percent of the predicted reliability rate. The V-22 was produced with a less-than-optimal hydraulic system because PMA-275 did not exercise sufficient oversight of the hydraulic system's design: PMA-275 did not specifically monitor the reliability rates of the hydraulic system's performance. As a result, the operational suitability of the V-22 *Osprey* was adversely affected. In addition to previously mandated design changes, other actions are needed to ensure sufficient management focus on the V-22 hydraulic system's performance and maintenance.

### Performance Criteria for the V-22

**Operational Requirements Document.** The Joint Requirements Oversight Council of the Joint Staff approved the "Joint Operational Requirements Document for the Joint Multi-Mission Vertical Lift Aircraft" on April 4, 1995. Change 1 was published May 19, 1999. The document established minimum accepted performance requirements for assessing the V-22's operational suitability. Operational suitability is the degree to which a system can be satisfactorily fielded, with consideration given to, among other factors, reliability.

**Specification Design.** Revision C of NAVAIR Specification Design 572-1, "Appendix B for V-22 Reliability and Maintainability" (SD-572-1), September 13, 1995 (as modified October 2, 2000), requires the contractor to conduct a reliability<sup>9</sup> program. SD-572-1 states that the Reliability Program Plan should include a "means for ensuring that the conclusions of reliability analyses result in appropriate changes to the equipment design to obtain the maximum inherent reliability." SD-572-1 prescribes design thresholds for reliability and requires that reliability predictions be calculated. SD-572-1 also references and restates portions of Military Standard 785B, "Reliability for Systems and Equipment Development and Production," which was initially published on September 15, 1980, and later modified on July 3, 1986, and August 5, 1988. Although Military Standard 785B was canceled on July 30, 1998, SD-572-1 incorporates requirements of the standard's Task 203 and Task 204.

Task 203, "Reliability Predictions," prescribed that reliability predictions be calculated using failure rate data approved by, or provided by,

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<sup>9</sup> Reliability refers to the probability that an item will perform its intended function for a specified interval under stated conditions.

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the procuring organization for a system, subsystem, and equipment to determine whether the mission reliability requirements could be achieved with the proposed design.

Task 204, “Failure Modes, Effects and Criticality Analysis (FMECA),” specified that a systematic and documented analysis be made of the causes and effects of failures and of likely scenarios in which a component or equipment could fail. Task 204 further required that the FMECA be performed to a specified level (such as the subsystem, equipment, part, or module level) and consider, among other factors, criticality (the failure’s impact on safety), readiness, mission success, and demand for maintenance logistics support.

Task 204 specified that a FMECA be completed concurrently with the design effort so that the design would reflect analysis conclusions and recommendations.

In addition to the FMECA process, SD-572-1 states that mean time between failure (MTBF) tests should “be performed to quantify the realistic target field performance of the mature aircraft weapon system and subsystems at the 5-digit WUC [work unit code<sup>10</sup>].” The V-22 hydraulic system has a 5-digit work unit code. SD-572-1 also requires that whenever design changes occur or test results indicate a difference between the predicted MTBF and the actual MTBF, the predicted MTBF should be revised to reflect the design changes or the test results. Different factors can be used in MTBF tests, and the results are commonly used to express reliability rates. The MTBF test discussed in this report is the “Mean Flight Hours Between Failure—Design Controllable,” which provides reliability rates that are the result of total flight hours (one measure of aircraft life) divided by the total number of design-controllable failures<sup>11</sup> during the measurement interval.

## Reliability Rates

The V-22 *Osprey* hydraulic system performed at reliability rates significantly lower than predicted by Bell Boeing. At best, during the EMD phase, the system achieved 38.2 percent of the predicted MTBF. (See Appendix C for a detailed explanation of our calculations, which incorporated learning curve

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<sup>10</sup> The work unit code is a 2- to 32-character numeric or alphanumeric code usually assigned to each repairable end item to identify a system, group, installation-repairable subassembly, or part of an end item in a hierarchical structure. A five-digit work unit code is assigned to those items that maintenance personnel would normally remove, replace, test, adjust, or repair while performing maintenance on the weapon system. Included among those are items that require portable test or repair shop equipment to maintain.

<sup>11</sup> Design-controllable failures are faults directly related to the design of the system. For example, a failure caused by an event or events outside the control of the designer, such as a bird strike or a deliberate removal of an aircraft part solely for engineering analysis, does not qualify as a design-controllable failure.

theory to arrive at percentages of predicted MTBF achieved.) The design of the hydraulic system was not changed significantly after it entered the EMD phase, even though the system performed at rates well below predicted levels.

The V-22 hydraulic system is composed of three independent subsystems: the primary Flight Control Hydraulic Systems, HYD-1 and HYD-2, and the Backup and Utility System, HYD-3. Table 1 shows the predicted and measured reliability rates of the three hydraulic subsystems and their respective hydraulic lines.

**Table 1. V-22 Hydraulic System Reliability Rates (MTBF)**

Hydraulic Subsystem	Predicted <sup>1</sup>		Measured		
	60,000 FHs <sup>2</sup>	2,000 FHs	EMD 1,581.1 FHs <sup>3</sup>	OPEVAL 804.5 FHs <sup>4</sup>	VMMT-204 569.1 FHs <sup>5</sup>
HYD-1	445	268	83	67	19
Lines	1,219	762	99	81	24
HYD-2	445	268	83	73	21
Lines	1,263	789	132	89	26
HYD-3	373	225	83	67	32
Lines	755	472	113	115	38

<sup>1</sup> Predicted reliability rates were developed by Bell Boeing.

<sup>2</sup> Flight hours.

<sup>3</sup> Flight hours accumulated by EMD aircraft from December 1996 through December 2000.

<sup>4</sup> Flight hours accumulated by LRIP aircraft during the OPEVAL, November 1999 through July 2000.

<sup>5</sup> Flight hours accumulated by LRIP aircraft assigned to VMMT-204 from March 2000 through December 2000 (excluding hours accumulated during the OPEVAL).

The predicted reliability rates for 60,000 flight hours (total flight hours for mature aircraft) and 2,000 flight hours (total flight hours for less mature aircraft) were developed by Bell Boeing, based primarily on historical operational data from other types of aircraft, factoring in a developmental learning curve. In the early stages of aircraft development, parts are expected to fail at higher rates than when the aircraft has accumulated thousands of flight hours. SD-572-1 notes that predicted reliability rates are to be revised whenever a design change in the system configuration occurs or when test results indicate a difference between the predicted and the actual MTBFs.

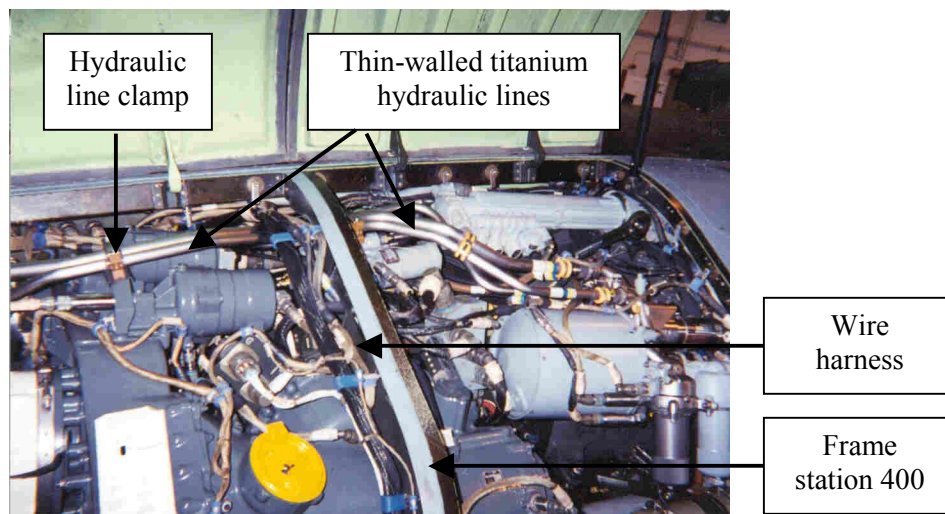
The measured reliability rates for the V-22 hydraulic system are the actual MTBFs of the components of each subsystem. For example, LRIP aircraft used for the OPEVAL accumulated a total of 804.5 flight hours and experienced 12 design-controllable failures of an HYD-1 component, resulting in a measured reliability rate of 67 flight hours. The HYD-1 hydraulic lines had a reliability rate of 81 flight hours. The lowest predicted reliability rate for HYD-1 was 268 flight hours; the lowest predicted reliability rate for HYD-1 hydraulic lines

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was 762. Table 1 shows that the V-22 hydraulic subsystems and hydraulic lines were performing at reliability rates lower than those predicted by Bell Boeing. Table 1 also shows a decline in measured reliability rates between EMD aircraft and LRIP aircraft assigned to VMMT-204.

## Compact Design of the Nacelle

The V-22 nacelles, located at the end of each wing, house the aircraft's engine and rotor system. The nacelles are densely populated with engine and rotor system components, including actuators, wire harnesses, and lines (including thin-walled titanium hydraulic lines<sup>12</sup>) that are intricately routed and in close proximity to one another. Because the hydraulic system is designed to operate at 5,000 pounds of pressure per square inch, it provides the opportunity to use smaller actuators and allows for a more compact packing of the nacelle. To achieve a lower aircraft weight, thin-walled titanium hydraulic lines are used in the nacelles and other locations throughout the V-22. Figure 2 illustrates the compact and heavily populated environment of the V-22 nacelles and identifies the frame station 400 as well as one of the many hydraulic line clamps, thin-walled titanium hydraulic lines, and wire harnesses within the V-22 nacelles.



**Figure 2. Outboard Right Nacelle of an LRIP Aircraft**

VMMT-204 maintenance personnel, the Line Clearance IPT, and the Panel indicated that the hydraulic system problems experienced by the V-22 Program were primarily caused by a compact nacelle design, which made it difficult to minimize the impact of vibration, and a manufacturing variance referred to as “artisan latitude.” Vibration and artisan latitude can result in hydraulic line chafing that degrades the reliability of the hydraulic system.

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<sup>12</sup> Hydraulic lines on the V-22 are made of a titanium alloy known as Ti-3AL-2.5V; the lines are referred to as Ti-3AL-2.5V 5,000 psi [pounds of pressure per square inch] tubing or 5,000 psi titanium tubing. This report uses the term thin-walled titanium hydraulic line to refer to that hydraulic tubing.



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**Vibration.** All aircraft—both rotary-wing and fixed-wing—experience vibration. Of those two forms of aircraft, however, rotary-wing aircraft experience the most intense vibration because they beat down air to overcome gravity and stay aloft. Although the V-22 experiences vibration in both the airplane and helicopter modes, the greatest level of vibration occurs when converting between the two modes. In particular, the Fleet Support Team (FST)<sup>13</sup> noted that the V-22 experienced extreme vibration levels in the nacelle areas. That vibration can lead to chafing, fretting,<sup>14</sup> and galling.<sup>15</sup>

**Artisan Latitude.** On the V-22, manufacturing variances occur primarily because of artisan latitude exercised by those who assemble aircraft. Artisan latitude refers to the ability of skilled workers to address conditions encountered while executing a task in their area of expertise. Two skilled workers may address an identical condition in two different ways. Conditions addressed by artisan latitude are usually of a minor nature and not specified in a blueprint or written instructions. Artisan latitude is a routine occurrence in any assembly process and usually has little impact on the finished product. However, the compact and heavily populated nacelles of the V-22 leave little or no room for workers to safely exercise artisan latitude. In addition, artisan latitude creates a lack of manufacturing repeatability that impacts logistics supportability, maintainability, and maintenance personnel training as well as degrades reliability by creating an unknown condition resulting from components that are not installed in a uniform configuration from one aircraft to another. A NAVAIR 3.0 Reliability-Centered Maintenance<sup>16</sup> Audit, finalized in May 2001, acknowledged, based on interviews with Line Clearance IPT personnel, that each V-22 LRIP aircraft was delivered with a different nacelle configuration, including numerous variations in the location and routing of hydraulic lines. The Panel and the Line Clearance IPT noted the lack of manufacturing repeatability between aircraft, a phenomenon primarily caused by artisan latitude.

**Hydraulic Lines.** Hydraulic lines on the V-22 are made of thin-walled titanium, a titanium alloy (Ti-3Al-2.5V) containing 94.5 percent titanium, 3 percent aluminum, and 2.5 percent vanadium. Developed in the late 1950s, thin-walled titanium is the industry standard for aerospace hydraulic lines primarily because of its strength-to-weight ratio; that is, its ability to provide adequate strength levels with a simultaneous reduction in weight. However, thin-walled titanium has unique characteristics and hazards that must be carefully considered in system design and installation. Hydraulic lines made with thin-walled titanium are extremely strong but are susceptible to chafing and have low wear limits. Other potential problems include fretting and galling.

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<sup>13</sup> The FST is an IPT assigned the responsibility to perform specified in-service engineering and logistics functions by the program manager.

<sup>14</sup> Fretting is caused by the combination of corrosion and wear, which is often seen in equipment with moving or vibrating parts.

<sup>15</sup> Galling is caused when the facing surfaces of two metal products meet. Excessive friction between the two surfaces can result in momentary adhesion and surface deterioration and can result in fretting.

<sup>16</sup> Reliability-centered maintenance is an analytical process used to identify and validate maintenance requirements of an aircraft weapon system to realize the reliability of the equipment at the least cost.

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**Hydraulic Line Chafing.** Hydraulic line chafing occurred when vibration caused hydraulic lines within the V-22 nacelle to rub against another surface, thereby causing the line to wear. Chafing is a common phenomenon among all aircraft and is not limited to hydraulic lines. However, chafing was a significant problem for hydraulic lines in the V-22 because of the extreme vibration levels encountered in the nacelles when the V-22 is operational and the difficulty of maintaining adequate clearance between hydraulic lines and other surrounding components, such as other hydraulic lines, wire bundles, nacelle partitions (including the frame station 400), and clamps used to secure the lines in the nacelle.

**Clamp Chafing.** On the V-22, chafing at clamping points (clamp chafing) was exacerbated by sand and dirt ingestion. Specifically, after vibration caused sand and debris in the vicinity of a hydraulic line clamp to become ingested between the grommet and the hydraulic line, continued vibration caused the sand and debris to chafe the hydraulic line within the grommet. To alleviate clamp chafing, Bell Boeing issued an engineering order on December 7, 1998, that directed the inspection and Teflon (tape) wrapping of hydraulic lines at 31 clamp locations. During the OPEVAL, conducted after the engineering order was issued, the Multi-Service Operational Test Team (Operational Test Team) encountered clamp chafing on LRIP aircraft. According to maintenance personnel, the Teflon wrapping reduced clamp chafing but did not eliminate it. NAVAIR officials stated that clamp chafing has been the subject of a series of engineering studies since May 2001. As of January 2002, the studies had not determined an adequate solution for the clamp chafing or pitting<sup>17</sup> experienced by the V-22.

A Bell Boeing-prepared analysis of VMMT-204 hydraulic line maintenance actions from March 2000 through March 2001,<sup>18</sup> covering 569.1 flight hours by the squadron's nine<sup>19</sup> LRIP aircraft, showed that 89 percent of all hydraulic line maintenance actions took place in the nacelles. Further, analysis of those actions attributed specifically to nacelle hydraulic line maintenance (140 maintenance actions that expended 664.2 maintenance hours) found that approximately 83 percent of those actions were caused by pitting or chafing. Table 2 shows a breakdown of the maintenance actions by problem.

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<sup>17</sup> On the V-22, pitting is a corrosive process that occurs on the titanium lines at a clamping area wrapped in Teflon tape. The studies have not been able to replicate or determine the cause of the pitting.

<sup>18</sup> The December 2000 grounding of the V-22 did not halt maintenance actions, which continued as a result of thorough inspections and already pending maintenance actions.

<sup>19</sup> In addition to the 8 LRIP aircraft assigned to VMMT-204, the analysis included an LRIP aircraft assigned to the squadron for about a month before joining the V-22 OPEVAL.

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**Table 2. VM MT-204 Nacelle Hydraulic Line Maintenance Actions**  
(March 2000 through March 2001)

<u>Problem Requiring Action</u>	<u>Percent of Actions</u>
Pitting under clamps (clamp chafing)	27
Chafing on wire harnesses	26
Chafing on lines or frame structures	18
Chafing on the frame station 400 baffle	12
Maintenance-induced errors	10
Leaking	7

Though hydraulic lines run under the floorboards and other areas of the V-22 fuselage, VM MT-204 had not encountered hydraulic line chafing in those areas to the same extent as in the nacelles. The Line Clearance IPT concluded that the hydraulic line and clamp chafing experienced by the V-22, particularly in the nacelle, was symptomatic of the contractor's inability to maintain adequate clearance between the hydraulic lines and other components when the V-22 was operational.

**The December 2000 Mishap.** Chafing was cited as a causal factor in the crash of a V-22 LRIP aircraft (Bureau No. 165440) on December 11, 2000. As of December 10, 2000, the aircraft, accepted into the V-22 Program in August 2000, had logged only 157.7 flight hours. The JAGMAN Report concluded that the rigid common hydraulic line made of thin-walled titanium in the left nacelle ruptured because the line chafed on wire harness W545 and was a causal factor in the mishap. PMA-275, in concert with the V-22 FST and the Hydraulics IPT, had established a wear allowance criteria of .002 inches for hydraulic lines. According to the JAGMAN Report, chafing wore away .007 inches of the ruptured lines .022-inch wall thickness.

The area of the nacelle where the hydraulic line and wire harness W545 are located is difficult to access and is not subject to routine inspection. The JAGMAN Report also stated that no squadron-level work had occurred in that area on the mishap aircraft. Of the 365 maintenance actions performed by VM MT-204 maintenance personnel on the mishap aircraft, 45 of the actions took place in the left nacelle. However, no work had been performed in the area of the hydraulic rupture.

According to the JAGMAN Report, a repeated chafing problem existed between the nacelle hydraulic lines and other components among all remaining V-22 LRIP aircraft. The JAGMAN Report cited various Airframe Bulletins, Hazardous Material Reports, and Quality Deficiency Reports from June 1999 through February 2001 that described a chafing problem of wire bundles and hydraulic lines in the nacelles of the V-22. The JAGMAN Report also stated that a VM MT-204 inspection of hydraulic lines found chafing conditions on all eight aircraft. In addition, the VM MT-204 inspection of LRIP aircraft Bureau No. 165441 found chafing on the same line that had ruptured in the mishap aircraft. Bureau No. 165441 had been accepted into the V-22 program in October 2000 and had only logged 83.7 flight hours.

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**Aircraft 21 Nacelle Audit.** In April 2001, the V-22 FST, in coordination with PMA-275, concluded an audit of the physical configuration of LRIP aircraft No. 21's nacelles (the Aircraft 21 Nacelle Audit). At the time, LRIP aircraft No. 21 was the next aircraft scheduled to be delivered to VMMT-204. The objective of the Aircraft 21 Nacelle Audit was to assess the as-built (actual) V-22 nacelle configuration with the as-designed (designed) configuration specified in the blueprints. In addition, the audit identified and analyzed instances where the nacelle design was problematic and required modification. As part of the audit, four work groups studied the nacelles' hydraulic, electrical, structural, and documentation areas. The hydraulics group inspected all hydraulic line installations in the nacelles, documented the results, including discrepant conditions (variances between the actual and designed configurations) and instances that might warrant a design change. The results of the Aircraft 21 Nacelle Audit provided V-22 Program officials with an indication of nacelle configuration problems and inconsistencies of V-22 LRIP aircraft.

As part of the Aircraft 21 Nacelle Audit, nacelle hydraulic line installations were inspected to document all variances with specification requirements. Only 138 (51 percent) of the 271 hydraulic lines inspected had been installed in accordance with design specifications. For the remaining 133 hydraulic lines, the hydraulics group identified 225 discrepancies between actual and designed configurations and attributed each to its root cause. Those discrepancies and root causes are shown in Table 3.

**Table 3. Discrepancies and Root Causes Identified by the Aircraft 21 Nacelle Audit Hydraulics Group**

Root Cause	Discrepancy	Number of Discrepancies	Percent of Total
Design	Drawing error	1	0
	Drawing needed clarification	3	1
	Design change needed	144	64
Manufacturing	Not installed per blueprint	8	4
	Workmanship	44	20
Other*		25	11
<b>Total</b>		<b>225</b>	<b>100</b>

\* Other includes instances such as an installed part that did not agree with the part specified in the blueprint, or an installed hydraulic configuration deviation from either V-22 specific or military hydraulic system design specifications.

**Design Issues.** Design issues were the root cause for 65 percent of all hydraulic line discrepancies. The Aircraft 21 Nacelle Audit hydraulics group identified 144 discrepancies requiring a design change. Those changes could include moving or rerouting a hydraulic line or moving a harness. The 144 discrepancies represented 64 percent of all discrepancies identified by the hydraulics group during the audit.

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**Manufacturing Issues.** Manufacturing issues were the root cause for 24 percent of all hydraulic line discrepancies. The hydraulics group identified 44 discrepancies (20 percent of all discrepancies) related to manufacturing workmanship problems. Those workmanship discrepancies were attributed to the “incorrect application of artisan latitude.”

According to one engineer for PMA-275, the findings of the hydraulics group and the other groups were among the first indications that a fundamental redesign of the nacelle might be warranted. Subsequently, the Line Clearance IPT developed a plan to redesign the nacelles to address nacelle hydraulic problems.

## Hydraulic Maintenance Training

V-22 maintenance personnel assigned to VMMT-204, as well as those who served on the Operational Test Team, were aware of the unique hydraulic system challenges posed by the use of thin-walled titanium hydraulic lines in the compact configuration of the nacelles. However, the VMMT-204 Technical Study Guide Program for V-22 maintenance personnel did not specifically cover those challenges.

Future V-22 maintenance personnel receive specialized V-22 maintenance training by attending the V-22 Fleet Replacement Enlisted Skills Training (FREST). FREST is an en route training program for specific weapon systems that provides training in familiarization, operation, and maintenance of the weapon system to be maintained. The V-22 FREST uses materials that are proprietary to Bell Boeing. V-22 FREST attendees have varying levels of maintenance training and include those with only the basic knowledge and skills required to perform basic maintenance on aviation systems at the squadron or organizational level as well as those with extensive maintenance experience gained through working on other aircraft platforms. Attendees, upon arrival at the V-22 FREST, complete a 3-day V-22 Aircraft Familiarization (Initial) Organizational Maintenance Course and then branch off into their specialized areas of V-22 maintenance training. Maintenance of the V-22 hydraulic system is included in the V-22 Airframes (Initial) Organizational Maintenance Course (the Airframes Course). Discussions with V-22 FREST officials and a review of the course materials revealed that the unique characteristics and hazards of thin-walled titanium hydraulic lines were only addressed verbally during the V-22 FREST.

Although titanium lines are similar in appearance to stainless steel lines, they cannot withstand the same level of wear and tear. Bell Boeing should amend V-22 FREST materials and VMMT-204 should modify its Technical Study Guide Program to include coverage of the unique characteristics and hazards of titanium hydraulic lines to further institutionalize awareness.

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## Oversight and Monitoring

The V-22 *Osprey* entered the LRIP phase in 1997 with a hydraulic system that performed at reliability rates significantly lower than predicted in the design process. PMA-275 did not exercise sufficient oversight of the hydraulic system's design: PMA-275 did not specifically monitor the reliability rates of the hydraulic system's performance.

During the EMD and LRIP phases, PMA-275 proactively monitored the aircraft's overall reliability to ensure the aircraft met reliability threshold requirements critical to the V-22 Program's progression to Milestone III (Full-Rate Production). PMA-275 also monitored frequently failing components. PMA-275 did not monitor performance of the hydraulic system to validate its predicted reliability. The Reliability IPT cited schedule and funding as factors that precluded the team from monitoring the performance of the hydraulic system. Furthermore, PMA-275 officials stated they did not track hydraulic system reliability at the component level because they believed that the risk associated with a failure of the system's components was low. That risk assessment was based on the hydraulic system's triple redundancy and the high reliability of the hydraulic system predicted by Bell Boeing. Although PMA-275 accepted the reliability rates predicted by Bell Boeing, PMA-275 did not validate those predictions with actual data to assess whether confidence in the hydraulic system was justified. The Panel's report stated:

The NAVAIR-detailed requirement for the V-22 specifies a total FCS [flight control system] reliability of one catastrophic failure in 10 million flight hours. Compliance with this requirement is demonstrated by analysis, which is the industry standard for this type of requirement. It is based on the system architecture (including redundancy), as well as predicted reliabilities for all components.

Although there was no written charter, Hydraulics IPT officials stated their mission was to oversee and to ensure the proper functioning of the hydraulic system. Specifically, the Hydraulics IPT was responsible for oversight of qualitative testing of all hydraulic system parts and for conducting laboratory qualification testing of titanium hydraulic line damage criteria. However, like the Reliability IPT, the Hydraulics IPT did not proactively or otherwise monitor the hydraulic system's measured reliability performance on EMD or LRIP aircraft. The Hydraulics IPT primarily responded to agenda items tasked by PMA-275 officials, as specified in annual Program Master Plans that detailed the anticipated Hydraulics IPT support to be provided to the V-22 Program. Although the Hydraulics IPT principally responded to PMA-275 taskings, hydraulic system problems were additionally brought to the Hydraulics IPT's attention—by the FST, the integrated test team,<sup>20</sup> Bell Boeing, and Hydraulics IPT members themselves. However, the Hydraulics IPT did not routinely

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<sup>20</sup> The integrated test team is a team comprising Government and Bell Boeing personnel responsible for developmental test flying of the aircraft.

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receive reliability information on the hydraulic system components from PMA-275 officials or from the Reliability IPT. PMA-275 should immediately establish a program to monitor the V-22 hydraulic system's reliability.

## V-22 Program Initiatives

After the December 2000 order grounding the V-22, PMA-275 began several initiatives, including the establishment of the Line Clearance IPT and the Senior Hydraulic System Review Team (the Senior Hydraulic Team), to identify and correct the challenges facing the V-22.

**Line Clearance IPT.** The Line Clearance IPT was established to identify, document, and study line clearance issues in the V-22 nacelles. Aside from focusing on potential avenues to limit chafing by ensuring that proper line clearances exist in each nacelle, the IPT was particularly interested in chafing under clamps. Once fixes have been agreed upon and approved, all fleet aircraft would be retrofitted, aircraft already produced but awaiting delivery would be modified, and production line changes would be implemented to apply the fixes to production aircraft.<sup>21</sup>

In August 2001, the results of the Line Clearance IPT's "90 Day Review" were briefed to NAVAIR and to the USD(AT&L). The Line Clearance IPT concluded that poor access, chafing (both under clamps and throughout the nacelle) because of insufficient clearances, and excessive maintenance hours per flight hour were major problems. In addition, the IPT stated that excessive maintenance hours per flight hour were symptomatic of maintenance personnel having to address problems of exceedingly poor reliability of hydraulic system components, a heavily populated nacelle, and insufficient access, all aggravated by the vibration typically encountered by rotary-wing aircraft.

**Senior Hydraulic Team.** The Senior Hydraulic Team was assembled to provide a thorough and independent technical review of the V-22 hydraulic system's architecture, including system design and validation. The Senior Hydraulic Team comprised retired engineers and industry consultants. The Senior Hydraulic Team began its assessment August 7, 2001, and published its results and recommendations January 5, 2002. The team concluded that the nacelle was a key problem area because of, among other factors, installation flaws, a lack of clearances, difficulty in inspecting hydraulic lines and installing or replacing components, and too many variances from one aircraft to another. The hydraulic line failure caused by chafing from a wire bundle was deemed a safety of flight issue. The team recommended that wire bundles be prohibited from being clamped to the hydraulic lines. The Senior Hydraulic Team made numerous other recommendations, including updating the critical parts list; developing criteria for critical part design, test, and installation; performing a

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<sup>21</sup> Production aircraft are new aircraft accepted from the contractor. They include all aircraft procured for operational or training purposes. Production aircraft do not include aircraft procured solely for experimental purposes.

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shaker test to locate chafing and ensure permissible line movement; and developing a tracking program for monitoring changes in clearances or configuration for hydraulic lines in the nacelle. Also, the Senior Hydraulic Team recommended that the re-design of the nacelle be accelerated; assembly of nacelle installations in the current configuration be stopped; and a plan be established to retrofit nacelle improvements into all existing aircraft.

PMA-275, in response to the problems identified by the Line Clearance IPT and the Senior Hydraulic Team, as well as by the Panel, developed a comprehensive strategy for correcting those problems. For example, production of the V-22 was reduced and a new developmental test, modification, and production plan was defined. The new plan is “event driven” as opposed to “schedule driven.” Key to the plan is completion of ongoing system laboratory tests, software upgrades, configuration modifications, and a comprehensive developmental flight test program that will thoroughly assess aeromechanical and reliability issues. The plan contains short-term and long-term actions that will improve overall nacelle configuration. Such actions include modifying internal nacelle components to meet hydraulic line clearance requirements, reduce chafing, and provide better physical access for inspection and maintenance of the nacelle. Other changes to be implemented include reducing the length of the common lines between the switching isolation valves and the swashplate actuators to reduce exposure of the lines to damage, designating those common lines as having “critical characteristics” as a means of ensuring quality during production and installation, and increasing the wall thickness of those common lines.

## **Conclusion**

The V-22 hydraulic system was designed with triple redundancy and its components had a high predicted reliability rate. Consequentially, PMA-275 decided to monitor overall aircraft reliability and frequently failing components rather than monitor the reliability of the hydraulic system to validate its predicted reliability. In retrospect, risks were underestimated and the hydraulic system’s poor performance adversely affected the V-22’s operational suitability through the EMD and the LRIP phases. During those phases, the measured reliability rates of the V-22 hydraulic system were well below the predicted rates. Because PMA-275 proactively monitored only the aircraft’s overall reliability, the hydraulic system problems indicated by low reliability rates were not addressed. In addition to ongoing redesign efforts, additional measures are needed to ensure sufficient management focus on the V-22 hydraulic system’s performance and maintenance.



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## Recommendations, Management Comments, and Audit Response

**1. We recommend that the V-22 Program Manager immediately establish a program to monitor the V-22 hydraulic system's performance, especially component reliability rates, on a continual basis. The program should, at a minimum, clearly delineate managerial and monitoring responsibilities of the offices and teams involved in the development and oversight of the V-22 Program.**

**2. We recommend that the V-22 Program Manager direct Bell Helicopter Textron, Inc., to amend all course materials for the V-22 Aircraft Familiarization (Initial) Organizational Maintenance Course of V-22 Fleet Replacement Enlisted Skills Training to include coverage of the unique characteristics and hazards of titanium hydraulic lines.**

**3. We recommend that the Commanding Officer, Marine Medium Tiltrotor Training Squadron 204 include coverage of the unique characteristics and hazards of titanium hydraulic lines in the squadron's Technical Study Guide Program.**

**Navy Comments.** The Assistant Secretary of the Navy (Research, Development, and Acquisition) concurred with the recommendations and stated that it has already established new hydraulic system reliability predictions for the first, in a series of three planned, aircraft upgrades and has established a process to monitor and report actual performance throughout the execution of the V-22's return-to-flight plan and continuing through fleet introduction. The Navy has also initiated action to modify MV-22 training modules for Initial MV-22 maintenance training to expand the modules' discussions of the unique characteristics and considerations of the titanium hydraulic lines. Furthermore, the Navy is updating its Technical Study Guide Program to emphasize the unique characteristics and considerations regarding conducting maintenance actions on or in the immediate vicinity of the titanium hydraulic lines. In addition, the Navy is staffing a Technical Publication Deficiency Report that will incorporate hydraulic line unique characteristic advisories to "all maintenance tasks performed on and around hydraulic lines" into the V-22's Interactive Electronic Technical Manuals.

The Navy also provided specific comments on various statements in the draft report. See the Management Comments section for the complete text of the Navy comments.

**Audit Response.** The Navy comments on the recommendations are responsive. We revised some statements in the draft report as a result of the Navy's specific comments.

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## Appendix A. Scope and Methodology

We interviewed officials from the Office of the USD(AT&L). We visited PMA-275 and interviewed staff to understand how they manage, assess, test, and correct problems associated with the V-22 hydraulic system. We obtained their perspectives on hydraulic system challenges and information on their initiatives to correct those challenges. We met with organizations that test, maintain, and operate the V-22. We interviewed members of IPTs supporting the PMA-275, including Reliability, Hydraulics, Line Clearance, and Safety IPTs, to determine the nature of their support of the V-22 hydraulic system. We met with directors of the MV-22 and the CV-22 Integrated Test Teams to obtain their perspectives on hydraulic system challenges, PMA-275's oversight of the hydraulic system, and initiatives to correct hydraulic system challenges. We interviewed Marine Corps and Air Force personnel who performed maintenance on the V-22 during the EMD phase and during the OPEVAL. We interviewed Marine Corps personnel at VMMT-204 about hydraulic system challenges on V-22 LRIP aircraft. We met with the commanding officers of VMMT-204 and of Detachment 1, 58th Operations Group, to gain their perspectives on the hydraulic system challenges faced by the V-22. We met with the V-22 FST that acts on behalf of PMA-275 and responds to VMMT-204 maintenance problems or anomalies with its LRIP V-22s. We met with the commanding officer and instructors from the V-22 FREST of the Naval Air Maintenance Training Group to determine current and proposed curriculum coverage of hydraulic systems in established maintenance courses.

To determine the nature, extent, and significance of V-22 hydraulic system challenges, we visited and interviewed officials at U.S. Marine Corps headquarters, NAVAIR, and VMMT-204.

We analyzed EMD, OPEVAL, and VMMT-204 hydraulic system component reliability data through March 2001 that was obtained from Bell Boeing to determine the measured hydraulic system component reliability for each phase. We analyzed VMMT-204 hydraulic line maintenance data from March 2000 through March 2001 to determine the types of problems requiring hydraulic line maintenance actions. We reviewed Naval Aviation Maintenance Discrepancy Reporting Program reports to determine the history of reported hydraulic system anomalies. We reviewed Chief of Naval Operations Instruction 4790.2H, "Naval Aviation Maintenance Discrepancy Reporting Program (NAMDRP)," June 1, 2001, to determine the established response times for acknowledging receipt of Naval Aviation Maintenance Discrepancy Reporting Program reports. We analyzed V-22 Integrated Test Team procedures to determine whether adequate policies and procedures were in place to govern the team's discrepancy resolution and feedback process. We analyzed various return-to-flight plan documents to determine the steps the V-22 Program is taking to address hydraulic system challenges. We reviewed V-22 test reports of hydraulic system performance during the EMD and LRIP phases. We reviewed the results of the Aircraft 21 Nacelle Audit to determine the nacelle hydraulic system design and manufacturing problems identified. We reviewed Aviation Board of Inspection and Survey (now the NAVAIR Technical Assurance Board)

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“Yellow Sheets” to determine the experienced reliability of hydraulic system components during developmental and operational testing. We also reviewed the Director, Operational Test and Evaluation, “Combined Operational Test and Evaluation and Live Fire Test and Evaluation Report on the V-22 *Osprey*,” November 17, 2000. We reviewed the V-22 functional maintenance plan to determine the scheduled maintenance requirements for the hydraulic systems and associated components. We reviewed the Panel’s report of April 30, 2001, and the JAGMAN Report, February 23, 2001, to determine the role hydraulic line chafing, artisan latitude, and Warnings, Cautions, and Advisories<sup>\*</sup> had in causing the mishap. We reviewed an April 25, 1997, USD(AT&L) Acquisition Decision Memorandum that approved the V-22 Program’s LRIP phase. We reviewed the May 14, 2001, USD(AT&L) memorandum to the Secretary of the Navy to document the reassumption of V-22 milestone decision authority by the USD(AT&L). We reviewed a December 21, 2001, USD(AT&L) memorandum to the Secretaries of the Navy and the Air Force and the Commander in Chief, U.S. Special Operations Command that detailed the V-22 return-to-flight plan. We reviewed the V-22 Program Status Report to Congress, April 2002, to determine the status of ongoing initiatives in support of the V-22 return-to-flight plan.

**High-Risk Area.** The General Accounting Office has identified several high-risk areas in DoD. This report provides coverage of the DoD Weapon Systems Acquisition high-risk area.

**Use of Computer-Processed Data.** We relied on computer-processed data contained in contractor and Government databases (or systems) established to track maintenance on the V-22 during the EMD and LRIP phases of development without performing tests of those systems’ general and application controls to confirm the reliability of the data. Specifically, our conclusions on the V-22 hydraulic system’s measured reliability during the EMD and LRIP phases up to the December 12, 2000, grounding were based on measured performance reliability rates obtained from Bell Boeing through the V-22 Reliability IPT.

We did not validate the accuracy of the Bell Boeing-generated reliability rates because of their general acceptance by V-22 Program officials. Most significant among those was the Reliability IPT, which concurred that the Bell Boeing-generated reliability rates for V-22 hydraulic system components were accurate and reliable, with some minor qualifications. In addition, we did not assess or validate the accuracy of the measured reliability rates because nothing came to our attention during the evaluation that caused us to doubt the reliability of the computer-processed data used to determine those rates. Further, we did not find errors or discrepancies that would preclude the use of the computer-processed data to meet the evaluation objectives.

**Use of Technical Assistance.** Using learning curve theory, members of the Quantitative Methods Division, Office of the Inspector General of the

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<sup>\*</sup> Warnings, Cautions, and Advisories are a series of the graphical, textual, and verbal messages that work in concert to succinctly pinpoint and communicate to the aircrew the root cause of an in-flight system failure or failures, and appropriate emergency procedures to correct those failure or failures.

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Department of Defense performed calculations on the Bell Boeing-predicted reliability rates and the measured reliability rates for the three hydraulic subsystems and their corresponding lines. The computations by the Quantitative Methods Division allowed comparison of the predicted and measured reliability rates (see Appendix C). Members of the Technical Assessment Division, Office of the Inspector General of the Department of Defense reviewed this report for technical content.

**Evaluation Dates and Standards.** We performed this evaluation from May 2001 through April 2002 according to standards implemented by the Inspector General of the Department of Defense. However, we did not attempt to meet the planning fieldwork standards because the evaluation process began as an audit assist to an investigation by the Defense Criminal Investigative Service, Office of the Inspector General of the Department of Defense into allegations of falsification of MV-22 aircraft maintenance and readiness records at VMMT-204. In addition, our scope was limited in that we did not include tests of management controls.

**Contacts During the Evaluation.** We visited or contacted individuals and organizations within DoD. We also contacted contractor personnel through their outside counsels. Further details are available on request.

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## **Appendix B. Prior Coverage**

During the last 5 years, the General Accounting Office and the Inspector General of the Department of Defense have issued five reports discussing the V-22. In addition, a four-member panel appointed by the Secretary of Defense issued a report on its independent review of the V-22 Program. Unrestricted General Accounting Office reports can be accessed over the Internet at <http://www.gao.gov>. Unrestricted Inspector General of the Department of Defense reports can be accessed at <http://www.dodig.osd.mil/audit/reports>.

### **General Accounting Office**

General Accounting Office Report No. GAO-01-369R, "Defense Acquisitions: Readiness of the Marine Corps' V-22 Aircraft for Full-Rate Production," February 20, 2001

General Accounting Office Report No. GAO-NSIAD-98-13, "Navy Aviation: V-22 Cost and Capability to Meet Requirements Are Yet to Be Determined," October 22, 1997

### **Inspector General of the Department of Defense (IG DoD)**

IG DoD Report of Investigation No. 200100549L-26-JAN-2001-03FA-PO/T, "Report of Investigation re: MV-22," July 9, 2001

IG DoD Report No. D-2000-174, "V-22 Osprey Joint Advanced Vertical Aircraft," August 15, 2000

IG DoD Report No. D-2000-115, "Protection of the V-22 Osprey Against RF Weapons (U)," April 24, 2000

### **Other**

"Report of the Panel to Review the V-22 Program," April 30, 2001

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## Appendix C. Learning Curve Calculations

### Mean Time Between Failure

As discussed in the Finding section, the MTBF test discussed in this report is the “Mean Flight Hours Between Failure—Design Controllable,” which provides reliability rates that are the result of total flight hours divided by the total number of design-controllable failures during the measurement interval. Table C-1 repeats Table 1 from the finding discussion.

**Table C-1. V-22 Hydraulic System Reliability Rates (MTBF)**

Hydraulic Subsystem	Predicted <sup>1</sup>		Measured		
	60,000 FHs <sup>2</sup>	2,000 FHs	EMD 1,581.1 FHs <sup>3</sup>	OPEVAL 804.5 FHs <sup>4</sup>	VMMT-204 569.1 FHs <sup>5</sup>
HYD-1	445	268	83	67	19
Lines	1,219	762	99	81	24
HYD-2	445	268	83	73	21
Lines	1,263	789	132	89	26
HYD-3	373	225	83	67	32
Lines	755	472	113	115	38

<sup>1</sup> Predicted reliability rates were developed by Bell Boeing.

<sup>2</sup> Flight hours.

<sup>3</sup> Flight hours accumulated by EMD aircraft from December 1996 through December 2000.

<sup>4</sup> Flight hours accumulated by LRIP aircraft during the OPEVAL, November 1999 through July 2000.

<sup>5</sup> Flight hours accumulated by LRIP aircraft assigned to VMMT-204 from March 2000 through December 2000 (excluding hours accumulated during the OPEVAL).

### Learning Curve Theory

Learning curve theory has traditionally been used in manufacturing industries. The theory assumes that due to the “learning” process, the cost per unit goes down with the increase in the number of units produced. In our calculations, we replaced the cost per unit with the average number of failures per flight hour, which, by theory, should go down as the number of hours goes up.

We used the classic learning curve equation ( $y_x = ax^b$ ), where  $a$  is the cost (in this case, the average number of design-controllable failures per flight hour) of the first flight hour,  $x$  is the number of flight hours,  $y_x$  is the average number of

failures of the  $x^{\text{th}}$  flight hour, and  $b$  is the mathematical value of the slope of the learning curve (defined by  $b = \log(\text{slope}) / \log(2)$ —the “2” comes from the doubling factor effect of the learning curve).

We used learning curve theory to calculate what the measured reliability rates should have been if the V-22 hydraulic system had achieved the rates predicted by Bell Boeing. We applied the learning curve theory to the Bell Boeing-predicted reliability rates. Using the classic learning curve equation, we determined the values for  $a$  and  $b$  that would result in the reliability rates Bell Boeing predicted for 60,000 and 2,000 flight hours. We then used those values to determine comparable predicted reliability rates for 1,581.1, 804.5, and 569.1 flight hours (the flight hours measured for EMD, OPEVAL, and VMMT-204 aircraft, respectively). Table C-2 shows actual, measured rates of those aircraft and the results of our calculations, the calculated reliability rates. The calculated reliability rates are the rates the three hydraulic subsystems and their corresponding lines should have achieved if they had performed as predicted by Bell Boeing.

**Table C-2. Measured and Calculated Reliability Rates**

Hydraulic Subsystem	Measured			Calculated		
	EMD 1,581.1 FHs	OPEVAL 804.5 FHs	VMMT-204 569.1 FHs	EMD 1,581.1 FHs	OPEVAL 804.5 FHs	VMMT-204 569.1 FHs
HYD-1	83	67	19	259	234	222
Lines	99	81	24	738	672	641
HYD-2	83	73	21	259	234	222
Lines	132	89	26	764	696	663
HYD-3	83	67	32	217	197	187
Lines	113	115	38	457	416	397

Table C-3 shows the percentages of predicted MTBF actually achieved by the EMD, OPEVAL, and VMMT-204 aircraft. As the table shows, the best percentage was realized by the Backup and Utility System (HYD-3) of the EMD aircraft and the worst was the hydraulic lines of one of the primary Flight Control Hydraulic Systems (HYD-1) of the VMMT-204 aircraft.

**Table C-3. Comparison of Predicted and Measured Reliability Rates**  
(percent of predicted rate achieved)

Hydraulic Subsystem	EMD 1,581.1 FHs	OPEVAL 804.5 FHs	VMMT-204 569.1 FHs
HYD-1	32.1	28.6	8.6
Lines	13.4	12.1	3.7
HYD-2	32.1	31.2	9.5
Lines	17.3	12.8	3.9
HYD-3	38.2	34.1	17.1
Lines	24.7	27.6	9.6

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## **Appendix D. Report Distribution**

### **Office of the Secretary of Defense**

Under Secretary of Defense for Acquisition, Technology, and Logistics  
Under Secretary of Defense (Comptroller)/Chief Financial Officer  
Deputy Chief Financial Officer  
Deputy Comptroller (Program/Budget)

### **Joint Staff**

Director, Joint Staff

### **Department of the Navy**

Assistant Secretary of the Navy (Manpower and Reserve Affairs)  
Assistant Secretary of the Navy (Research, Development and Acquisition)  
Naval Inspector General  
Auditor General, Department of the Navy  
Program Executive Officer, Air Anti-Submarine Warfare, Assault, and Special  
Mission Programs  
V-22 Program Manager

### **Department of the Air Force**

Assistant Secretary of the Air Force (Financial Management and Comptroller)  
Commander, Air Force Special Operations Command  
Auditor General, Department of the Air Force

### **Marine Corps**

Commandant of the Marine Corps  
Commanding Officer, Marine Medium Tiltrotor Training Squadron 204  
Inspector General of the Marine Corps

### **Unified Commands**

Commander in Chief, U.S. European Command  
Commander in Chief, U.S. Pacific Command  
Commander in Chief, U.S. Southern Command  
Commander in Chief, U.S. Central Command  
Commander in Chief, U.S. Special Operations Command



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## **Non-Defense Federal Organization**

Office of Management and Budget

## **Congressional Committees and Subcommittees, Chairman and Ranking Minority Member**

Senate Committee on Appropriations  
Senate Subcommittee on Defense, Committee on Appropriations  
Senate Committee on Armed Services  
Senate Committee on Finance  
Senate Committee on Governmental Affairs  
House Committee on Appropriations  
House Subcommittee on Defense, Committee on Appropriations  
House Committee on Armed Services  
House Committee on Government Reform  
House Subcommittee on Government Efficiency, Financial Management, and Intergovernmental Relations, Committee on Government Reform  
House Subcommittee on National Security, Veterans Affairs, and International Relations, Committee on Government Reform  
House Subcommittee on Technology and Procurement Policy, Committee on Government Reform

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